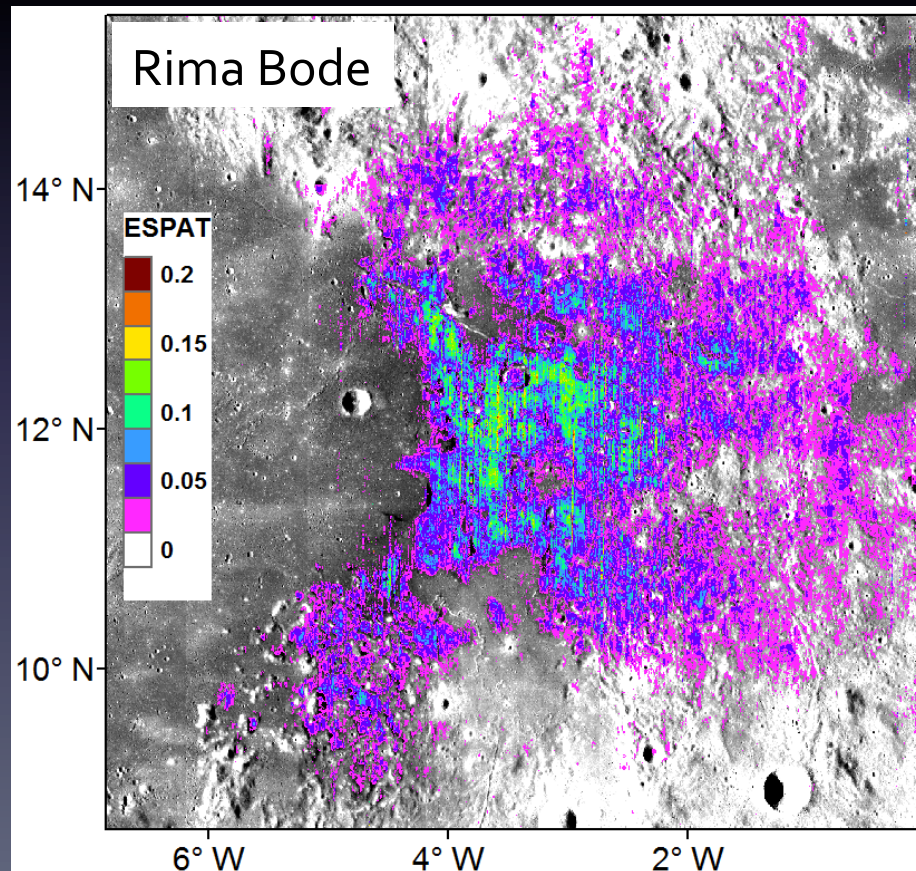


Quantitative mapping of hydration in lunar pyroclastic deposits and implications for lunar volcanic processes

Shuai Li and Ralph E. Milliken



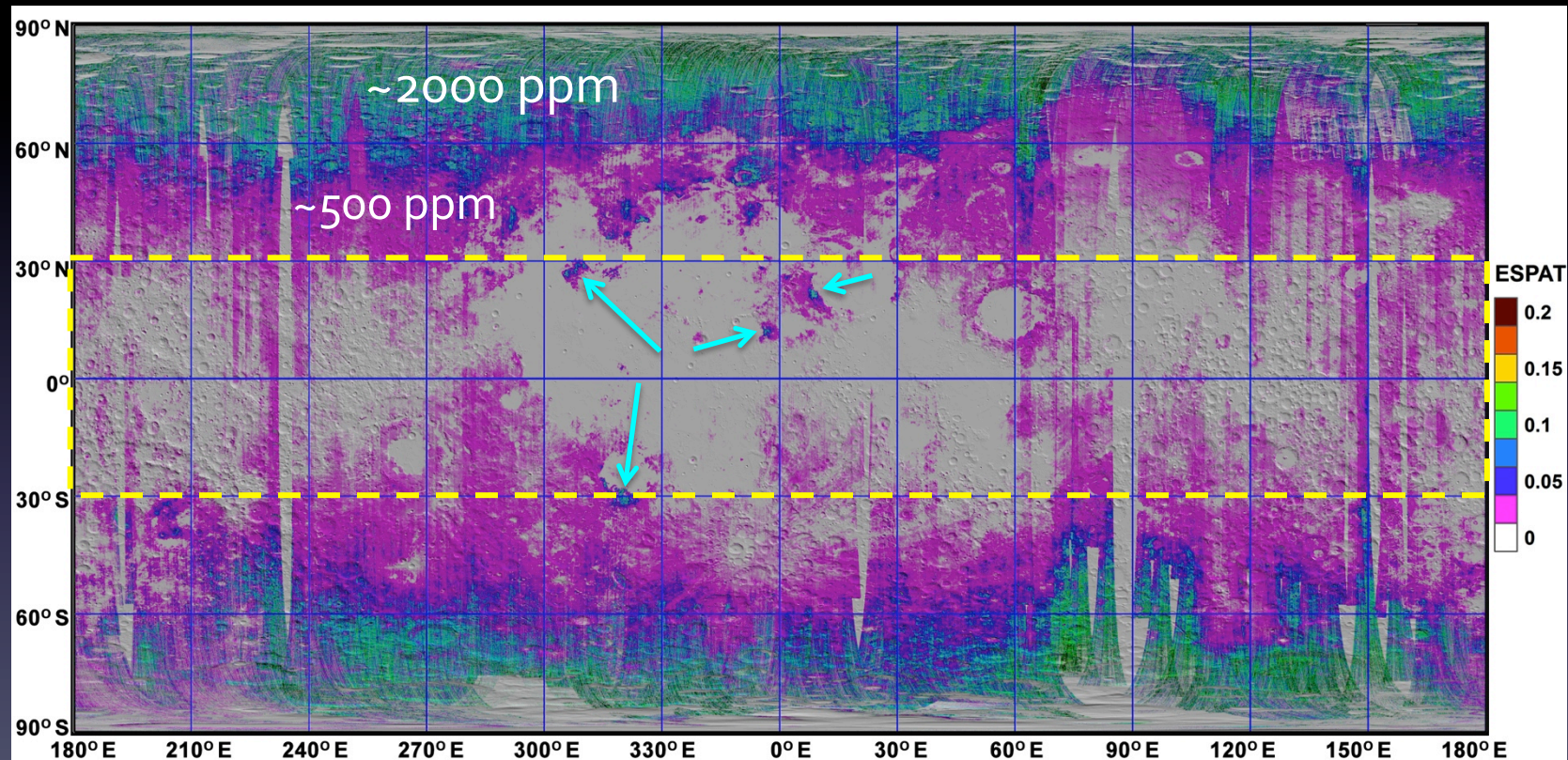
BROWN

Planetary Geosciences
Group



Introduction

- We are in a process of **quantifying** lunar surface hydration with newly thermal corrected M³ images [Li and Milliken, 2012;2013;2014]



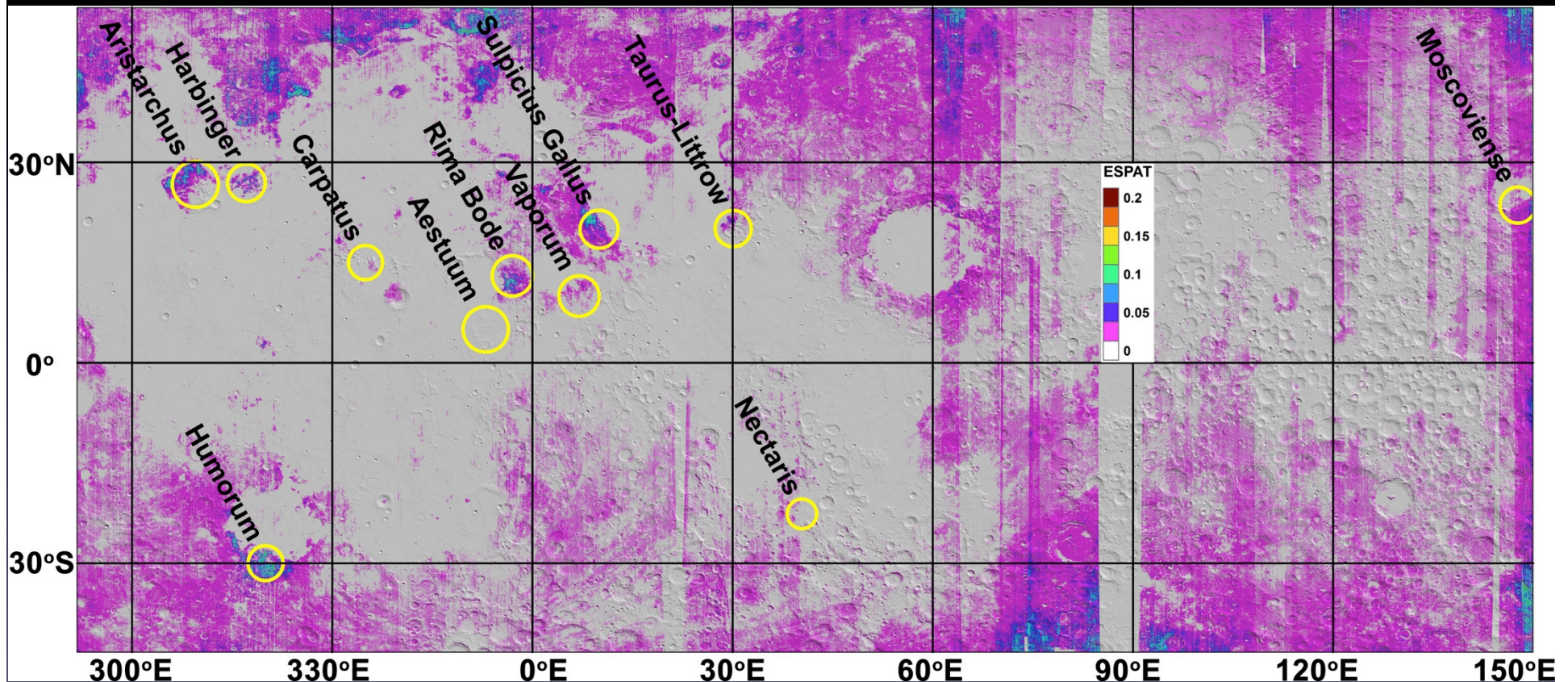
- Lunar surface hydration exhibits strong variation with latitude.
- Preliminary lab experiments imply 500-2000 ppm in bulk 'soil'.
- Weak / no hydration between $\pm 30^\circ$ latitude at local noon....***except pyroclastics!***



BROWN

Hydration in Pyroclastic Deposits

- Most pyroclastic deposits exhibit hydration levels significantly higher than background levels (up to ~1000 ppm assuming basaltic glass).



= 11 large pyroclastic deposits (>1000 km²)
[Gaddis et al., 2003] between ±30° latitude

Objectives

- To answer these questions:
 - How is the hydration in pyroclastic deposits retained over geological timescales (i.e., Ga)?
 - Which factors control the spatial variation of hydration in individual pyroclastic deposits?
 - Volcanic glass abundance, water content of glass, or both?
 - What do water contents of different pyroclastic deposits tell us about volcanic processes and magma volatile content?
 - We can compare our estimated hydration levels with pyroclastic emplacement models [*e.g. Wilson and Head, 2014*] and lunar sample data [*e.g., Saal et al., 2008*].

Methods

- Post-emplacement diffusion models for water in glasses
 - Hydration diffusion modeling

$$\frac{\partial C}{\partial t} = \frac{\partial}{\partial x} \left(D \frac{\partial C}{\partial x} \right) \quad (1)$$

$$D(T) = \exp\left(-12.97 - \frac{13939}{T}\right) \quad [\text{Zhang and Ni, 2010}]$$

- Modeling lunar sub-surface temperature [*Mitchell and De Pater, 1994; Vasavada et al., 1999*]

$$\frac{\partial T}{\partial t} = \frac{1}{\rho C(T)} \frac{\partial}{\partial x} \left(K(T) \frac{\partial T}{\partial x} \right) \quad (2)$$

- Quantifying volcanic glass abundances [*Li et al., 2012*]
 - A BPNN model trained with the Lunar Soil Characterization Consortium dataset (mineralogy, chemistry, reflectance spectra)

Methods

- Compare our estimated hydration values with:
 - Volatile abundance ($n1$) derived from the model of *Wilson and Head, 2014*

$$n1 = \frac{Rgm(\gamma - 1)}{2QT\gamma} \quad (3)$$

R : pyroclastic range

g : gravity

m : gas molecular mass

γ : heat capacity ratio

Q : gas constant

T : magmatic temperature

- Volatile abundance ($n2$) derived from mass conservation [*Wilson and Head, 2014*]

Deposit volume

Melt volume in magmatic "foam"

$$Ad\rho_{deposit} = (L_D W_D D_D f)\rho_{melt}$$

$$n2 = \frac{\rho_{gas}(1-f)}{\rho_{melt}f + \rho_{gas}(1-f)} \quad (4)$$

A : deposit area

L_D : dike length

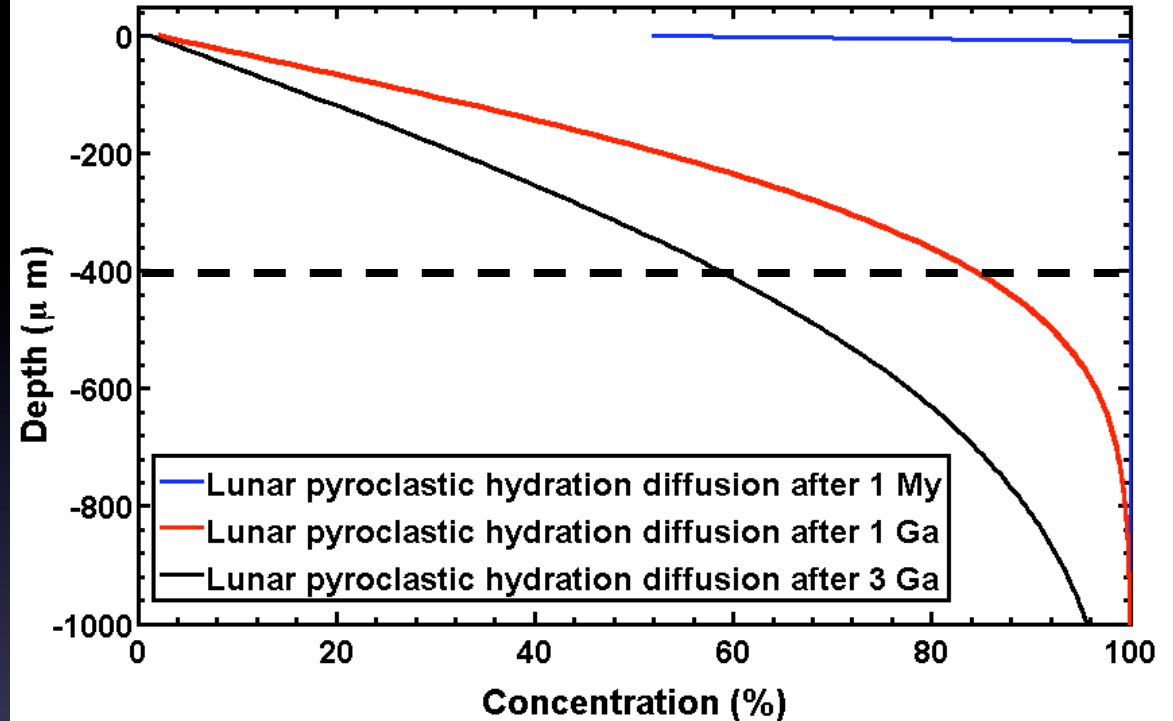
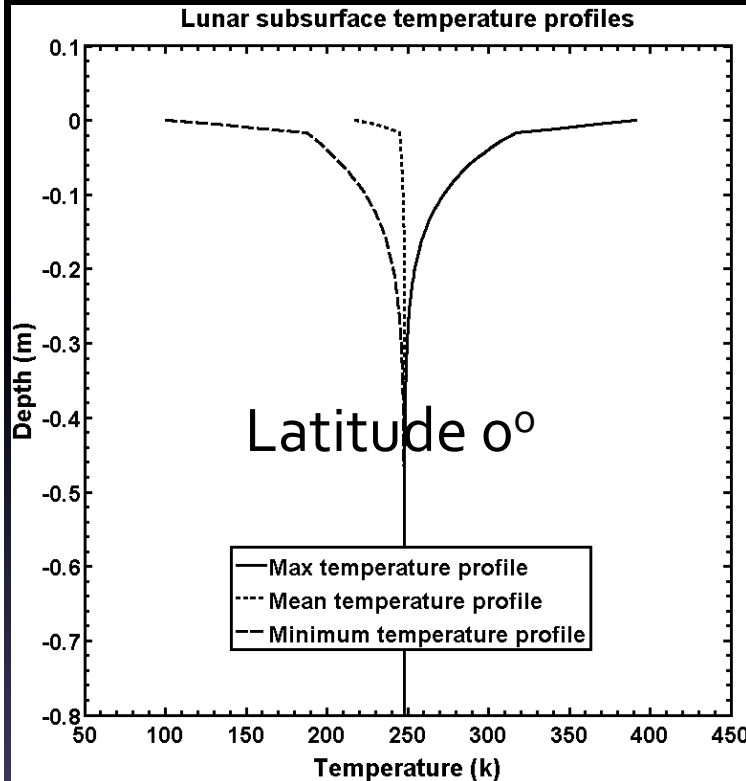
W_D : dike width

D_D : dike depth

f : melt fraction

Pyroclastic deposit thickness (d) is derived from LROC NAC images based on diameter-depth ratio of superposed craters

Post-emplacement Diffusion of Water

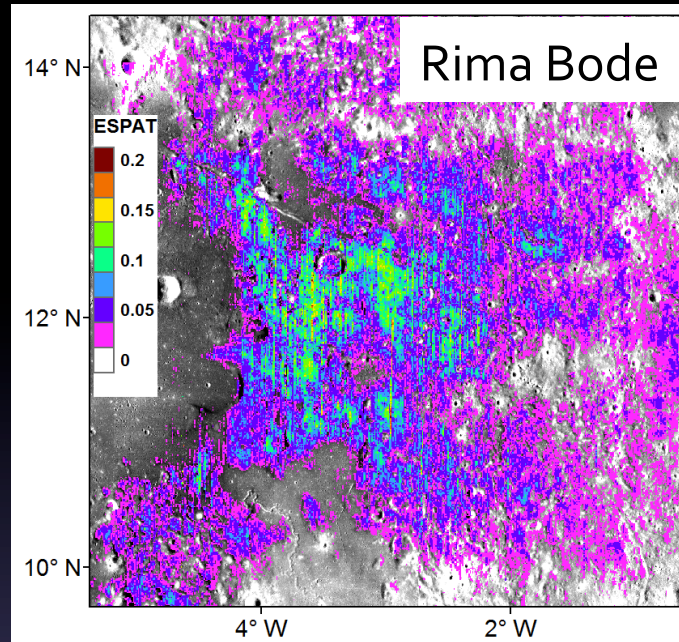


Simplest case: at an optical depth of $\sim <400 \mu\text{m}$ we expect at least 60 – 90% hydration will be retained after 1-3 Gyr exposure.

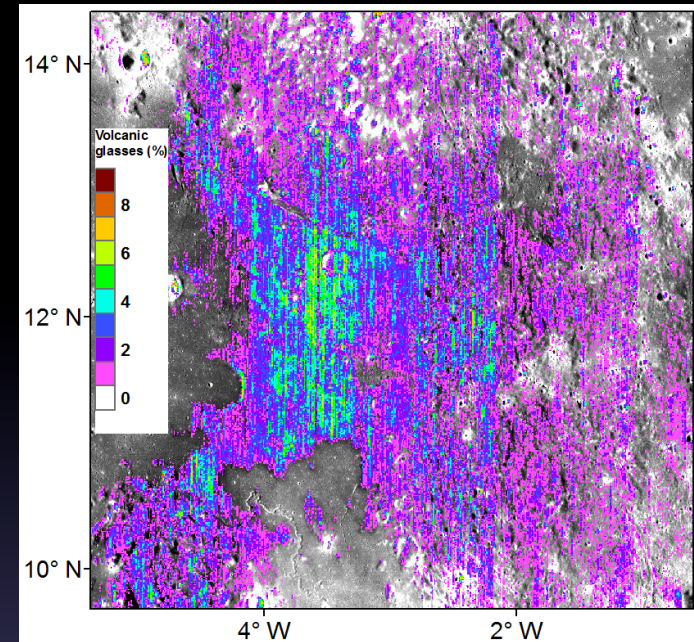
But, porosity, permeability, surface adsorption will affect the diffusion process and will be considered in future models.

Hydration vs. Volcanic Glass Abundances

Hydration

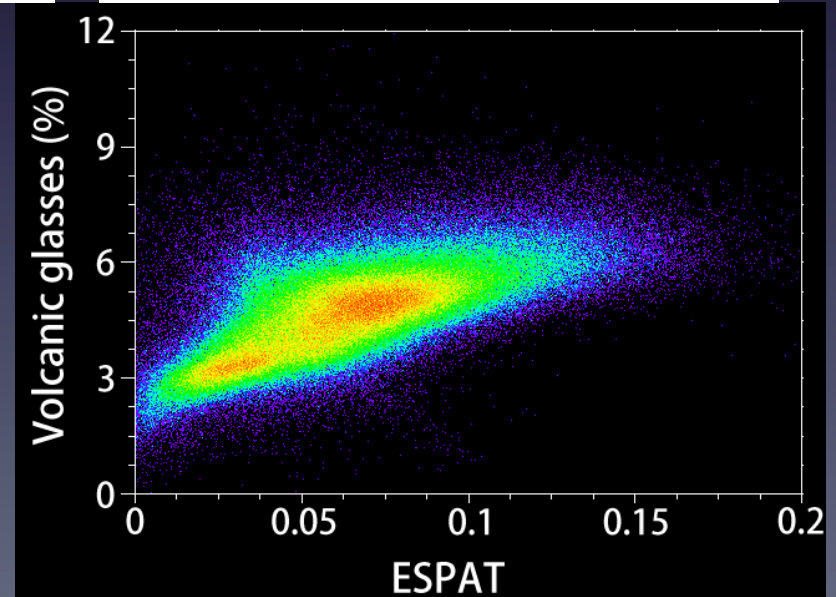


Volcanic glasses



If the glass has a ~constant water content, then glass *abundance* will be a primary factor controlling the observed bulk hydration level.

[We use Hapke's ESPAT parameter as a proxy for bulk water content of soil]



Estimated VS. modeled hydration (1)

Maximum range clasts were ejected: ~73 km

From *Wilson & Head* [2014] model we can calculate total volatiles:

R: pyroclast range = 73 km

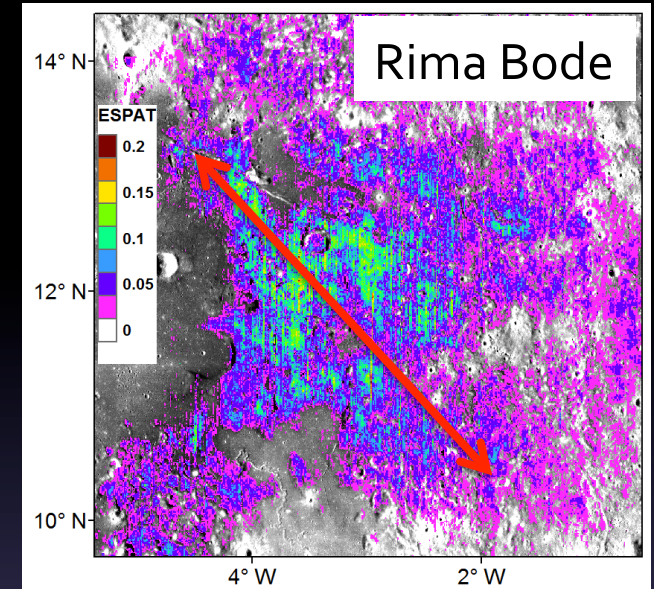
g: gravity acceleration = 1.622 m/s²

m: gas molecular mass = 28 g/mol

γ: heat capacity ratio = 1.3

Q: gas constant = 8.314 J/(K•mol)

T: magmatic temperature = 1600 K



$$n1 = \frac{73000 * 1.622 * 28 * 0.3}{2 * (8.314 * 1000) * 1600 * 1.3} \approx 29000 \text{ ppm}$$

Only ~1% of volatiles is likely water [*Wetzel et al., 2014*]:

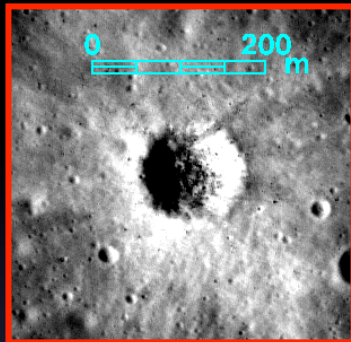
Hydration = 290 ppm; retained after 1-3 Gyr diffusion, **174 – 261 ppm**

Our average estimation: ~210 ppm

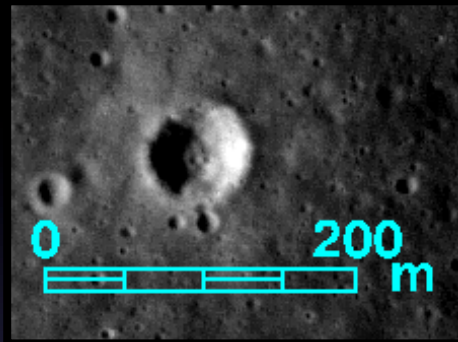
Thickness of pyroclastic deposits

1. Classifying craters

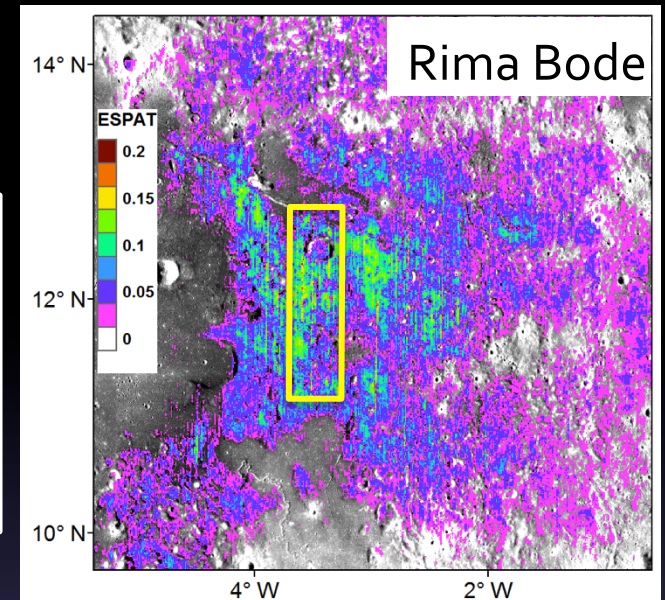
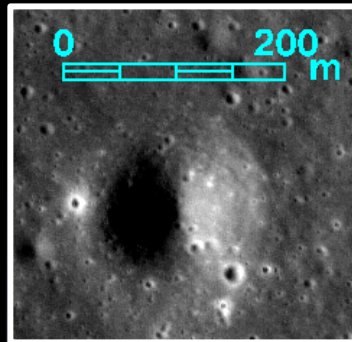
Penetration



No Penetration



Not counted



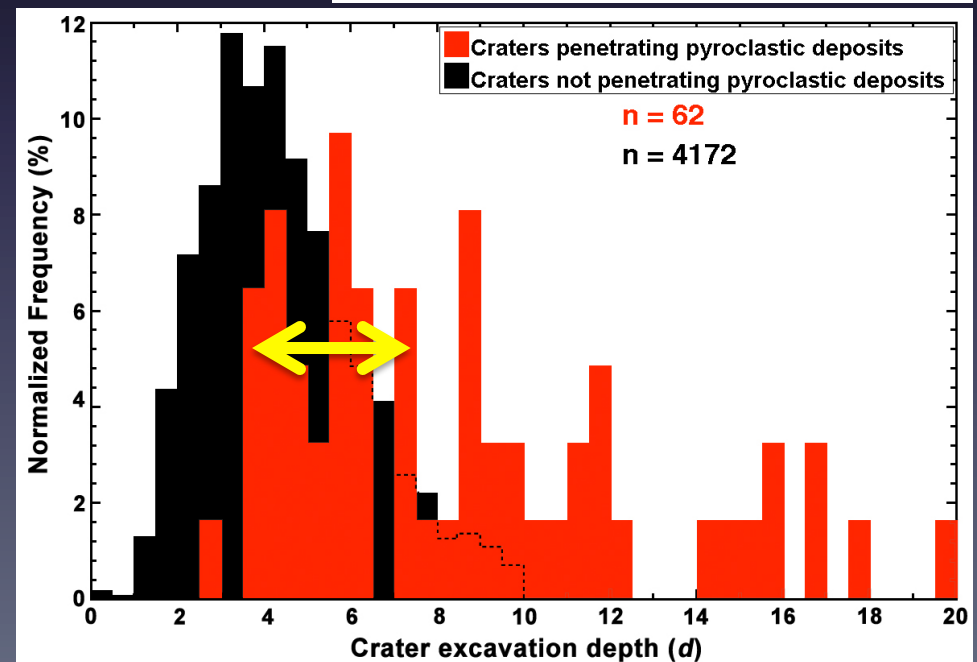
2. Criteria:

- Choose smooth regions
- Avoid ejecta blanket of large craters

3. Results:

- Craters < 4 m do not excavate underlying material
- Thickness is locally heterogeneous

Max. thickness: ~4 - 8m





BROWN

Estimated VS. modeled hydration (2)

Area: $\sim 15000 \text{ km}^2$

Approximate dike length: 60 km

With equation (4), we can estimate volatile
[Wilson and Head, 2014]:

L_D : dike length = 60 km; W_D : dike width = 300 m

D_D : dike depth = 8000 m; $\rho_{melt} = 3000 \text{ kg/m}^3$

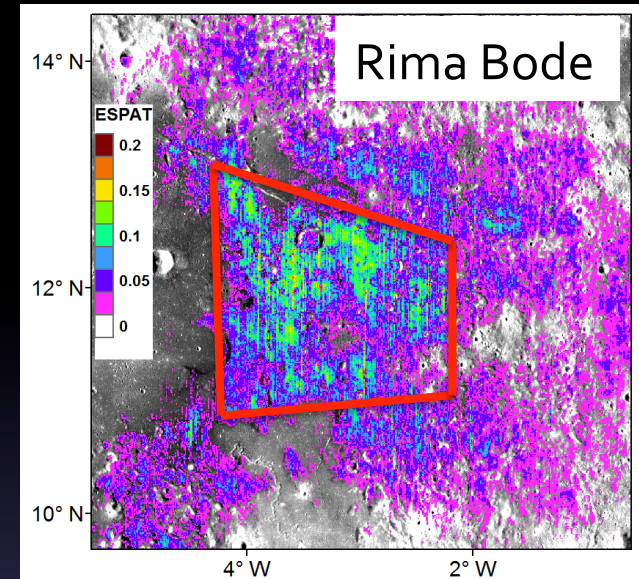
$\rho_{deposit} = 2000 \text{ kg/m}^3$; $d = 4 - 8 \text{ m}$; $\rho_{gas} = 40 \text{ kg/m}^3$

$$f = \frac{Ad\rho_{deposit}}{(L_D W_D D_D)\rho_{melt}} = \frac{15000 * 1e6 * (4 \rightarrow 8) * 2000}{(60000 * 300 * 8000) * 3000} = 0.28 \rightarrow 0.49$$

$$n_2 = \frac{\rho_{gas}(1-f)}{\rho_{melt}f + \rho_{gas}(1-f)} = \frac{40[1 - (0.28 \rightarrow 0.49)]}{3000(0.28 \rightarrow 0.49) + 40[1 - (0.28 \rightarrow 0.49)]} = 14000 - 33000 \text{ ppm}$$

Modeled water content (1% of total): 140 – 330 ppm

Our estimated average hydration: $\sim 210 \text{ ppm}$



Conclusions

1. Simple post-emplacement diffusion models confirm that significant water contents in pyroclastic deposits can be retained over geological timescales. Future models will integrate porosity, permeability, etc.
2. Hydration abundances in pyroclastics are linearly correlated with volcanic glass abundance (e.g., Rima Bode, Sulpicius Gallus)
 - Indicates hydration is endogenous from the lunar interior (magmas)
 - Glass water content presumably varies, but glass abundance is key for bulk water content
3. Our estimated hydration values are consistent with those derived using recent pyroclastic emplacement models [*Wilson and Head, 2014*]
 - Water content measured at the surface can be related to magmatic processes & volatile contents of source regions.

Backup slides



BROWN

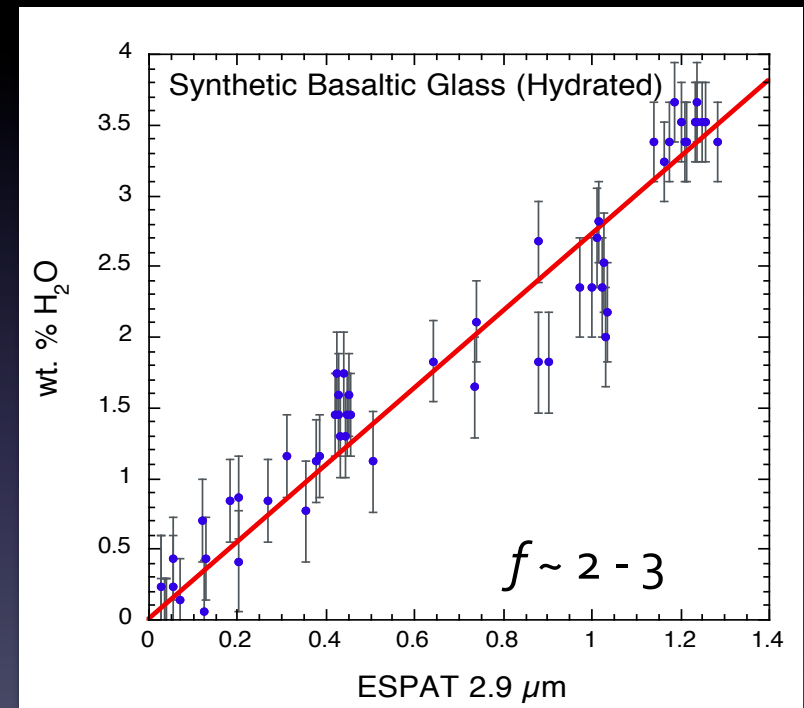
Methods-Mapping hydration

- Hapke's **Effective Single Particle Absorption Thickness** (ESPAT)

parameter exhibits a linear relationship with water content for a wide variety of minerals (*Milliken & Mustard 2005, 2007a, 2007b*).

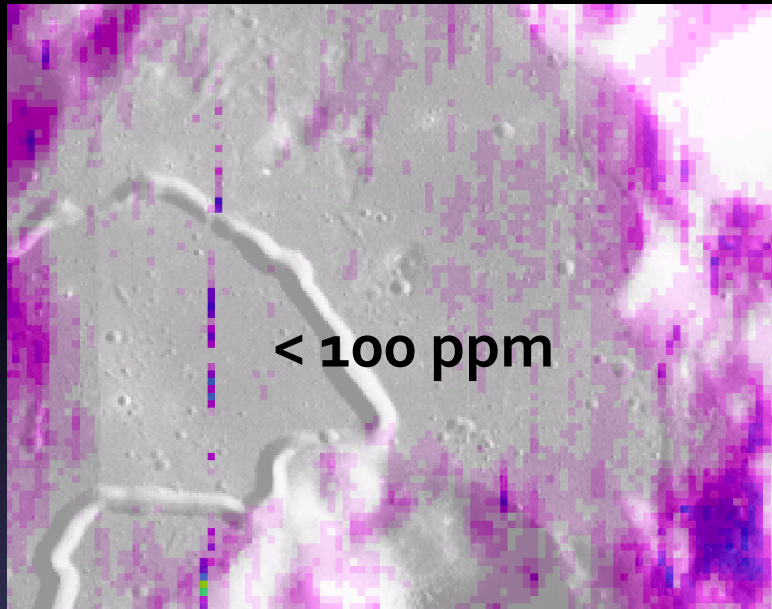
- For hydrated basaltic glass and many other materials, the ESPAT-H₂O trend has a slope of ~2.5; value may be different for anorthosite.

$$ESPAT_{2.9\mu m} = \frac{1 - \bar{\omega}_{2.9\mu m}}{\bar{\omega}_{2.9\mu m}}$$

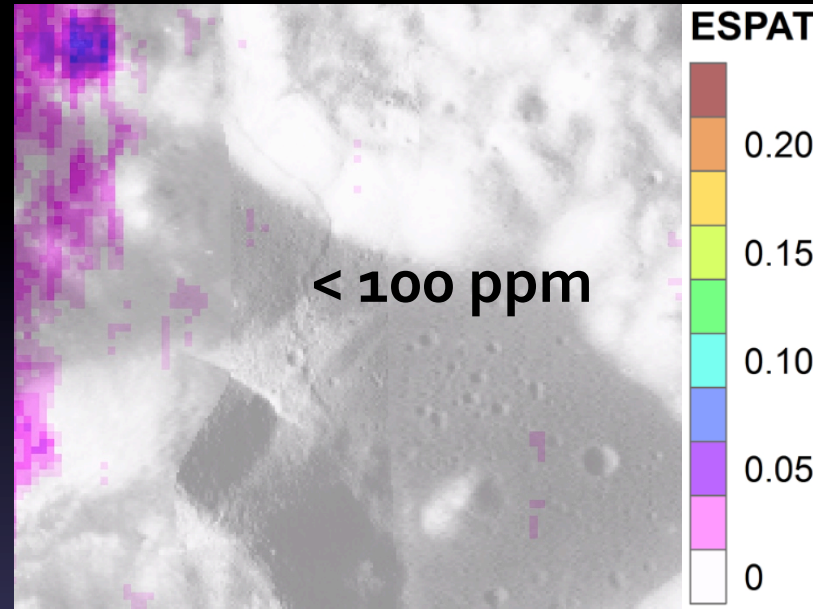


- The ESPAT parameter can be used as a proxy for water content.

Apollo 15 and 17 landing sites hydration

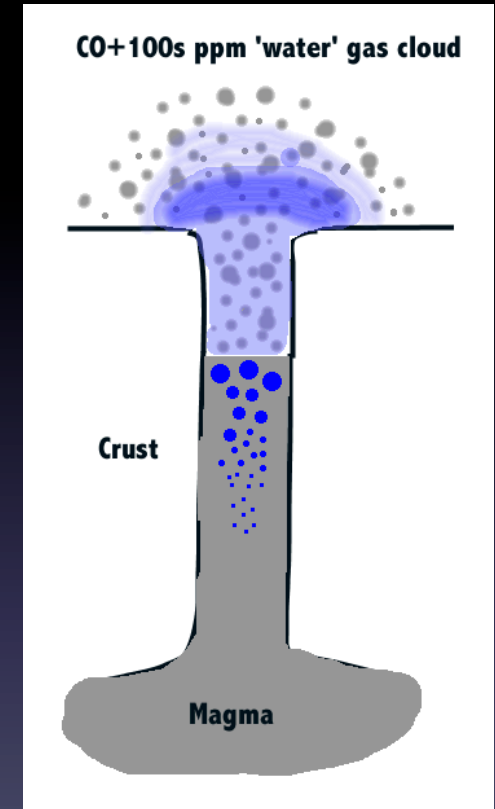
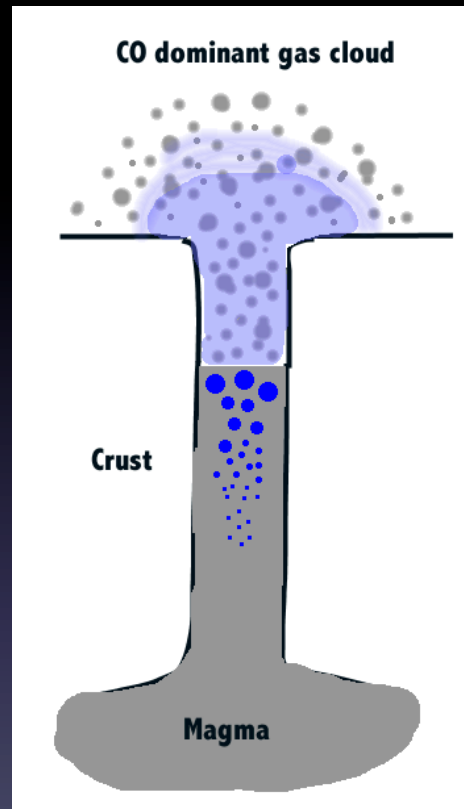
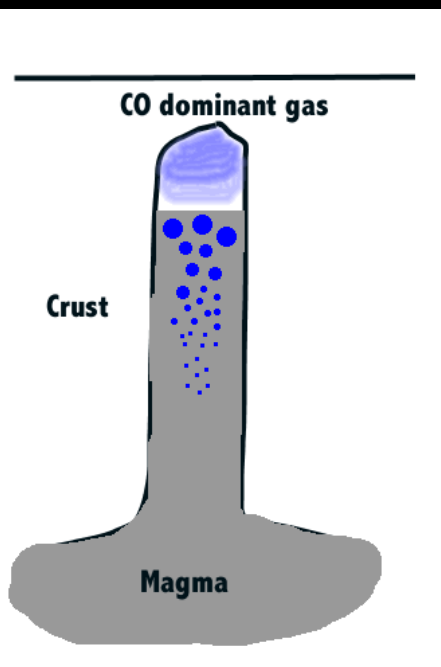


Apollo 15 landing site



Apollo 17 landing site

Hydration variation through pyroclastic emplacement



After the first several minutes, 'water' in melts drops from 1000s ppm to 10s ppm by diffusing [Saal *et al.*, 2008]. Assuming magma takes 30% volume, 100s ppm 'water' is in the gas cloud.

The 'water' will slow down the diffusion process of magma 'water'.

Future work

- We will map volcanic glasses at the rest pyroclastic deposits to compare with our estimated hydration.
- We will estimate the thickness of the rest pyroclastic deposits with the LROC NAC images to understand how pyroclastic thickness affects on hydration levels.
- We will do more investigations to understand the retention of hydration during volcanic eruptions.